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ESTIMATION OF LONG-TERM PROBABILITIES FOR INADVERTENT INTRUSION INTO RADIOACTIVE WASTE MANAGEMENT AREAS: A REVIEW OF METHODS

by

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PROJECT TEAM

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ABSTRACT

The risk to human health from radioactive waste management sites can be calculated as the product of the probability of accidental exposure (intrusion) times the probability of a health effect from such exposure. This report reviews the literature and evaluates methods used to predict the probabilities for unintentional intrusion into radioactive waste management areas in Canada over a 10,000-year period. Methods to predict such probabilities are available. They generally assume a long-term stability in terms of existing resource uses and society in the management area. The major potential for errors results from the unlikeliness of these assumptions holding true over such lengthy periods of prediction.

ABRÈGÉ

Le risque provenant des sites de contrôle de déchets radioactifs peut être calculé comme étant le produit de la probabilité d'exposition accidentelle (intrusion) par la probabilité d'un risque pour la santé par une telle exposition. Ce rapport passe en revue la documentation et évalue les méthodes utilisées pour prédire les probabilités d'intrusions involontaires sur des aires de contrôle de déchets radioactifs au Canada sur une période de 10,000 ans. Des méthodes pour prédire de telles probabilités sont disponibles. Une stabilité à longue échéance en termes d'utilisation de ressources existantes et de société est généralement supposée dans la région de contrôle. Le plus grand risque d'erreur provient du fait que ces suppositions pourraient se révéler fausses pour de si longues périodes de prédictions.

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SECTION 1

INTRODUCTION

1.0 INTRODUCTION

Radioactive wastes of various types in Canada are currently, or will likely in the future, be disposed of by means of shallow, intermediate and deep geologic disposal. If institutional controls lapse in the future, there is a finite probability that accidental intrusion into one of these sites may occur. The public health significance of this intrusion will depend upon the nature of the intrusion and the consequent radiological or chemical exposure that may occur. The risk resulting from accidental intrusion at disposal sites is thus the product of the probability of accidental intrusion times the probability of a health effect occurring as a result of the intrusion.

The objective of this study is to review and discuss methodology(ies) that various groups have used or may use for estimating the probabilities of various scenarios of inadvertent human intrusion into different types of waste disposal facilities. This provides an approach to the first part of the two-part risk equation. It is worth noting that many authors have taken the approach of initially assuming an intrusion probability of one and then calcualting the resultant radiation dose. If the resultant dose is insignificant, then there is no need to spend time and effort calculating an intrusion probability which, by definition, cannot exceed one.

In order to provide a standard reference point for illustration scenarios and the discussion of methodologies for estimating probabilities of intrusion, it is necessary to make some assumptions. These assumptions centre around the concept that persons in the future will behave and carry out land use activities similar to those which are being carried out today.

Activities such as:

- farming, land clearing and urban development,
- burying of power cables, gas lines, foundations for large buildings and reservoir construction, or
- mining exploration, deep tunneling and geothermal resource development.

May reasonably be expected to result in probabilities of an accidental intrusion into surface, intermediate and deep waste repositories.

It is possible that developments over the next several decades or century may make these types of activities obsolete, and society may not bear any resemblance to what we know today. A more highly 'advanced' society may reasonably be expected to be able to identify and then to 'cope' with or avoid altogether accidental intrusion. Lower technology societies would have less chance of circumventing intrusion barriers incorporated into the design of such disposal sites. The highest risk (product of intrusion probability times health detriment) would thus appear to exist for a society similar to that found in 'advanced' countries today, where intrusion technologies are more widespread than knowledge of consequences at the individual worker level if no risk is suspected (i.e., the intrusion is truely accidental).

It would thus seem reasonable to conclude that, if probabilities of intrusion are calculated based upon present-day accidental intrusion technologies, the highest risk level may be expected to be derived from the calculations.

SECTION 2

STUDY METHODS

2.0 STUDY METHODS

The major tasks in this study involved identification, retrieval and critical review of the pertinent literature.

2.1 Information Retrieval

Three main methods were used to identify and retrieve literature relative to the appropriate methodology for prediction of intrusion probabilities:

- a search of computer databases;
- contacts with regulatory agencies, consultants and facility operators involved with radioactive waste management; and
- a review of reference lists, symposiums, etc. from relevant publications.

Computerized information databases searched during this study are listed in Table 2.1. Searches were conducted through the Canadian Institute for Scientific and Technical Information (CISTI) in Ottawa. A list of several hundred references was generated from which about 30 were found to be relevant to this study. These and other references reviewed are listed in Section 7.0.

Contacts were made with a variety of regulatory agencies, nuclear waste management facility operators and researchers in the United States and Canada. These groups are also identified in Section 7.0 of this report. Most of the relevant work had been done at institutions in the U.S.A. in the late 1970's or early 1980's. As a result, few people were still available at these institutions who could remember these studies or the titles of relevant reports. The U.S. Nuclear Regulatory Commission's Facilities Management Institute identified and supplied the key documents from this period of research. Several U.S. university researchers currently active in the field were also contacted and supplied their most recent literature. This field of research is not currently very active. No Canadian research on analysis of probabilities for intrusion into radioactive waste management sites was identified.

A large portion of the relevant literature was identified through references cited in papers obtained through the above searches. Several abstracting services or conference

TABLE 2.1: COMPUTER DATABASES SEARCHED

Database	Coverage
NTIS	U.S. Government Reports (1964 to present) - over one million references
EIM	Engineering Meetings (1979 to present) - about one-half million references
ENVIROLINE	Environmental Literature (1971 to present) - over 100,000 references
EI	Engineering Index (Compendex) (1970 to present) - over one-half million references
INIS	International Nuclear Information (1970 to present) - over one million references
POLLUTION ABSTRACTS	Pollution (1970 to present) - over 100,000 references

proceedings were also reviewed, including: Owen et al. (1986), Kocher (1982), Ainslie (1986), the Canadian Nuclear Association Second International Conference on Radioactive Waste Management (1986), Proceedings of Waste Management '83, Symposium on Management of Low-Level Radioactive Waste (Atlanta, 1977), and the Symposium on Waste Management and Fuel Cycles (Washington, 1979).

2.2 Literature Review and Reporting

The critical review of literature and preparation of this report were conducted by Beak Consultants Limited. An external advisory committee was set up to advise the authors during the study and review the report. This consisted of members from the University of Waterloo Institute for Risk Research and from the AECB.

2.3 Study Strategy

The approach followed in this study was to review a broad base of literature on intrusion, and then narrow the focus to what were considered 'reasonable' intrusion scenarios for the Canadian content. Based upon these scenarios, a review of the approaches used to estimate probabilities of intrusion were carried out, along with a discussion of how these methodologies may be used.

SECTION 3

INTRUSION SCENARIOS AND APPROACHES USED TO ESTIMATE PROBABILITY OF ACCIDENTAL INTRUSION

3.0 INTRUSION SCENARIOS AND APPROACHES USED TO ESTIMATE PROBABILITY OF ACCIDENTAL INTRUSION

Predictions of the probabilities for intrusion scenarios are most important where such scenarios can result in significant radiological impacts. Some authors have argued that, if the radiological impact for an assumed intrusion is acceptable, an analysis of the probability of intrusion is not required.

This section focuses on the intrusion scenarios for each disposal category which may result in significant risks. The dosimetry modelling techniques used to evaluate these risks have not been reviewed in this study. These scenarios which could result in the most significant radiological impacts, if they occur, are felt to be the scenarios for which probability analyses of intrusion are most relevant. Probability analysis techniques that may be applicable to intrusion are discussed in Section 5.0.

3.1 Intrusion Into a Deep Repository

The general consensus is that surficial land uses, such as farming or inhabitation, on a deep disposal site will not involve activities which could result in a significant probability of intrusion exposure. This assumes that the site is properly designed, and that radioisotopes do not escape into local groundwater pathways at unacceptable rates which could result in a form of secondary intrusion. The assumptions are also made by most authors that:

- with intentional intrusion to recover the waste for reuse, the risk is the responsibility of the intruder; and
- for most intrusion scenarios into a deep repository, a high level of technical capability is required; this technical knowledge level is assumed to be adequate for the intruders to monitor and identify radiological risks before significant exposure occurs.

Based upon the literature, the following four intrusion scenarios are judged to result in significant radiological impact, and thus the probability of their occurrence is important in determining the risk potential. These scenarios are:

- o salt solution mining;
- o exploratory drilling and/or excavation for minerals;
- o drilling for petroleum resources; and
- o geothermal drilling.

3.1.1 Salt Solution Mining

This is an intrusion scenario which has received considerable research interest in the U.S.A. and the U.K. The scenario has incorporated a variety of potential exposure pathways, including mining and distribution of contaminated salt to a large population, opening of pathways to allow contaminant movement into nearby aquifers, and exposure of exploration crews. Since this is not a concept currently proposed for Canadian radioactive waste disposal, it is not detailed in this report. There are, however, significant mineral deposits in Canada which are currently being solution mined and many others which have the potential to be. Those who are interested in further details are referred to Battelle Memorial Institute (1981), Lawson (1983), Woolfolk and Baer (1983), Intera Technologies (1985), Little (1979 to 1980), Harper and Raines (1985), and Battelle Pacific Northwest (1980).

3.1.2 Mineral Exploration

Davis and Runchal (1984) utilized a Delphic panel approach to estimate relative probabilities for intrusion into a Hanford weapons waste repository in deep Basalt. The Delphic panel methodology involved the assembly of an 'expert' panel which volunteered their opinions. The relative probabilities of intrusion were then calculated based upon the 'consensus probability' as determined by the panel. One-third of the panelists felt that deep mining had a high probability of resulting in an intrusion into this area over the long-term. This was the only intrusion scenario felt to possibly result in significant radiological impacts, and thus the only scenario worthy of evaluation. Further risk evaluation was left to future studies. Gillis (1985) reached a similar subjective conclusion that mineral exploratory drilling was the only credible scenario for direct intrusion into a deep repository. They 'felt' that anyone with the technology to conduct such deep exploration would identify the risk as soon as samples were brought to the surface for logging and analysis, thus minimizing potential exposure problems. Dixon (1985) 'felt' that depths of 50 m or more with engineered barriers would provide perpetual

resistance to intrusion. The Human Interference Task Force (1984) also concluded that geological exploration or mining were the only credible intrusion scenarios for a deep geological waste repository. They felt that, with the measures proposed to isolate such wastes, a society with an inferior technology would not be capable of accessing the waste repository. A society with an equal or superior technology should be capable of identifying wastes if they are hit during bedrock drilling, and would identify the risk and take precautions prior to significant exposure. Cameron (1981) also assumed that any society with the technology to find resources 600 m underground will have the technology to determine and avoid the risks. All of these approaches avoid the determination of accidental intrusion probability by using the approach of assuming it is one and then evaluating the risk on that basis.

Little (1979 to 1980) provide one of the most extensive analyses of potential contaminant release mechanisms relative to a deep radioactive waste repository. Many other U.S. authors use the Little probability calculations as a starting point for their intrusion risk calculations. Only one type of deep repository intrusion scenario was felt to be credible, drilling. A variety of drilling scenarios was described:

- oil and gas exploration;
- deep water wells;
- geothermal exploration;
- drilling wells for deep injection disposal of wastes;
- mineral exploration;
- salt solution mining;
- scientific exploration; and
- preparation for storage of a liquid resource.

Statistics on drilling rates for different bedrock types to depths greater than 300 m in the U.S.A. were found to be:

- Granite: 3.8×10^{-4} to $3.8 \times 10^{-3}/km^2$,
- Basalt: 6.3×10^{-3} to $1.6 \times 10^{-2}/km^2$, and
- Shale: 3.8×10^{-3} to $7.5 \times 10^{-1}/km^2$.

The Little report concluded that most exploratory drilling is preceded by geophysical research which might identify the location of a repository and result in precautions. Further, they believed that borehole logging, geochemical or geophysical testing are likely to identify a radiation risk if a fuel bundle or repository structure is hit. They do develop what they consider as the most likely accidental intrusion scenario for a deep repository, with the following characteristics:

- o although the site is chosen to avoid known resources, some unpredicted resource becomes scarce and valuable in the future causing exploratory drilling in the repository area;
- o drilling is intensive over a relatively short period of time as the resource is exploited and depleted;
- o the intensive exploration occurs soon after the 100-year institutional control period specified by the U.S. EPA. The report authors feel this is ultraconservative, since it is doubtful that knowledge of the site would be lost so soon, and since this represents a maximum period for potential exposure;
- o the scenario includes drilling for any of a variety of existing valuable resources and assumes variable levels of these resources in the repository area. Hydrocarbons vary from none to presently uneconomic or too deep to recover. Water varies from only present at deep levels to abundant near the surface. No presently economic ores are found in the area, nor is there a geothermal anomaly with the exception of the repository itself;
- o drilling rates in the first century after loss of institutional control is between five to 50 holes per century per 8 km^2 area. This decreases to two to five holes per century after this period;
- o the waste disposal area is 8 km^2, fuel bundles are 0.15 m in diameter, and 35,000 of these are randomly distributed throughout the site area; and
- o boreholes are 0.1 m in diameter.

Merkhofer and Keeney (1987) summarize the conclusions of the U.S. Department of Energy on deep disposal intrusion potential. Probabilities were estimated by pooling the subjective estimates of a panel of experts who had been trained in probability estimation. Details of how these probability estimates were pooled were not provided in this paper. The results, discussed in Section 5, can be summarized as:

- o No deep disposal intrusion scenario resulted in unacceptable risks of exposure;
- o Intrusion scenarios were judged to have a much lower probability of resulting in radioactive exposure than the geophysical aspects of the site; and
- o The only intrusion scenario judged to have any probability of resulting in exposure was exploratory drilling into a salt bed disposal site. Intrusion through exploration drilling into other (not salt bed) media was "judged to be extremely unlikely" and given a probability of 0.

3.1.3 Petroleum Drilling

Little (1979 to 1980) reported that petroleum drilling rates in the U.S.A. average 0.005 holes per km^2 per year deeper than 385 m. This statistic is used in their drilling scenario discussed above. They do emphasize the limitations on such probability estimating techniques with a reference to the history of petroleum exploration. A hundred years ago, there was no petroleum drilling, and there have been over two milliion holes drilled since.

3.1.4 Geothermal or Scientific Drilling

Little (1979 to 1980) noted that the history of geothermal drilling or deep scientific exploration drilling is too short to develop any reliable statistics for predicting future rates. Cameron (1981) felt that curiosity over the heat source is a potential cause for intrusion into a high-level repository.

3.1.5 Summary

Based upon the current Canadian deep geologic disposal concept, the most likely accidental intrusion scenarios would include:

- o geothermal or drilling,
- o mineral exploration, and
- o scientific exploration.

Based on the literature reviewed and the conclusions reached by research in the U.S.A., these scenarios are all very unlikely with probabilities near zero.

3.2 Scenarios for Intrusion into a Shallow Repository and Uranium Mill Tailings

Much of the intrusion research in the U.S.A. has related to shallow land burial of radioactive wastes from a variety of sources. No relevant American reports were found on uranium mill tailings intrusion scenarios, but most of these would be similar from a probabilistic approach, with the major differences being exposures once intrusion occurred.

Based on the literature reviewed the following scenarios were judged most representative of long-term, inadvertent, intrusion into a shallow repository:

- o farming/dwelling,
- o excavating/constructing (including mineral exploration), and
- o archaeology/treasure hunting.

3.2.1 Farming/Dwelling Intrusion Scenario

This is the most commonly investigated scenario for intrusion into a shallow, low-level burial site (Virginia and Christie, 1981; Pinner and Hill, 1982; U.S. NRC, 1981; Hansen and Rogers, 1983; Rogers et al., 1986). Both Pinner and Hill (1982) and Sandquist and Rogers (1986) presented evidence, based on historical uses of vacant lands, that an isolated farm dwelling is a much more likely accidental intrusion scenario than an urban residential development.

The farming/dwelling scenario usually assumes a number of combined exposure pathways:

- o resuspension and inhalation of surface soils during cultivation;
- o direct gamma exposure;
- o drinking water from a local well; and
- o eating locally produced crops and meats.

In some cases (Pinner and Hill, 1982; Hardy and Dixon, 1986), accidental intrusion includes excavation to construct farm buildings.

In most of these studies, the intrusion probability is assumed to be one after an initial institutional control period, and the risk based upon this. If the probability of one times the risk consequence of intrusion is acceptable, then the disposal technology is considered acceptable. Hunter and Lester (1984) relate intrusion probabilities directly to waste burial depth with 1 metre burial intrusion $p = 1 \times 10^{-5}$/yr. This is divided by depths in metres for probabilities at deeper burial depths. Sandquist and Rogers (1986), based upon extrapolation, existing land use patterns in the state, adjusting for future trends, provide calculations for the time required for the intrusion scenario probability to increase to one for disposal in Idaho, as follows:

- pasture and grazing use - 1,000 years;
- cropland - 5,000 years; and
- residential - 100,000 years.

3.2.2 Excavation/Construction Scenario

Dickmand and Boland (1983) labelled accidental intrusion through excavation as an "improbable worst case" scenario. Pinner and Hill (1982) calculate probabilities for a variety of construction activities (recreational, utility, residential, business, service) based on the existing rate of vacant land utilization in the U.K. They establish overall construction probabilities for any single year which decline from 3.4×10^{-3}/year at year 10 to 4.5×10^{-4}/year for the 500th year after disposal. These are about 1,000 times less than their calculations for the probability of the land being farmed. Sandquist and Rogers (1986) estimated residential construction/use potential based upon past and current land use for an Idaho disposal site at 100 to 20 times less than the agricultural use probability.

3.2.3 Shallow Burial and Uranium Mill Tailings Intrusion Scenario Summary

Although numerical probabilities of intrusion are not given for uranium mill tailings, Walsh has identified a series of possible accidental intrusion scenarios. The Nuclear Energy Agency (1982) made a brief comment on potential intrusion into uranium mill

tailings disposal areas. They noted that intrusion is a "possibility that must be considered, and should be controlled either by local, state or national regulatory agencies". Regarding probability analysis for intrusion, the NEA had the following statements:

- o 100 years is the maximum extent that one can rely on engineered facilities;
- o 1,000 years after disposal is the "period beyond which it may be reasonably expected that geomorphological, climatological, institutional and technical awareness are so unpredictable that further prediction is meaningless"; and
- o 10,000 years after disposal is the "time frame during which geomorphological stability of a region may have changed to such an extent that further projection becomes meaningless".

In Canada, about 9 million tonnes, or less than 1% of the tailings disposed to date, have been used as mine backfill or placed in deep-lake disposal (Feenstra et al., 1985). These could be considered similar to deep disposal from an intrusion scenario analysis viewpoint.

Based on the above, three types of intrusion scenarios are most representative for the shallow land burial scenario:

- o Farming/Dwelling Scenario,
- o Excavation Scenario, and
- o Recreational Exposure Scenario.

SECTION 4

DATA ON EXISTING LAND USES IN CANADA RELEVANT TO PREDICTING FUTURE INTRUSION POTENTIAL

4.0 DATA ON EXISTING LAND USES IN CANADA RELEVANT TO PREDICTING FUTURE INTRUSION POTENTIAL

Most evaluations of the long-term probabilities for accidental intrusion into radioactive waste disposal sites are based on extrapolation of existing land uses and resource values. This assumes no significant changes in many factors such as climate, societal technology, population, etc. over a period of usually 10,000 years. Although this assumption is tenuous at best, it is a necessary starting point. This chapter reviews some of the data sources relevant to land uses and resource values in Canada which could be used as a starting point in quantitative evaluations of probabilities for intrusion into Canadian waste disposal areas.

4.1 Waste Disposal Areas

Three types of disposal were discussed in Section 3.

- Deep disposal of spent reactor fuel or high-level waste in a granite pluton at a depth of 500 to 1,000 m.
- Shallow disposal of intermediate to low-level wastes. As currently proposed, a site could be the size of a shallow land disposal facility described as approximately 100 m by 20 m by 8 m (Hardy and Dixon, 1986).
- Uranium mill tailings are by far the bulk of the radioactive wastes in Canada. Due to the volume and area of these wastes, there is no proposal to move them from their existing locations, nor bury them to a significant depth (> 2 m).

Uranium mill tailings in Canada are found entirely within the Canadian Shield. There are an estimated 635 ha of uranium mill tailings growing at about 5% per year. Tailings are distributed about 81% in the Elliot Lake area, 14% in northern Saskatchewan and 5% in the Bancroft area.

The Canadian high-level repository is currently proposed to be located in the Canadian Shield region of northern Ontario. Wastes likely to be deposited by shallow burial include refinery and other miscellaneous low level wastes. The 9 ha of refinery wastes in the Port Hope, Ontario area, are located in an area of sand and clay lacustrian deposits

overlying Ordovician bedrock. The shallow low level waste buried area at Chalk River is also located in a sandy outwash area.

Radioactive waste disposal in Canada is and is expected to be confined to a small number of areas, mostly in the Canadian Shield and, with the exception of Saskatchewan tailings, almost all in Ontario. Thus, for estimation of future land uses or resource exploration/extraction, these are the important locations.

4.2 Regions of Canada

Statistics Canada (1986) provides a summarization of much of the Canadian demographic data needed to predict future land uses. The statistics are provided following two types of regional subdivision, by ecoregion (Figure 4.1) and by drainage basin (Figure 4.2). The ecoregion approach lends itself better to the requirements of this study and will be used in the following examples. The drainage basin approach utilizes smaller subdivisions, and thus might be more appropriate for site-specific evaluations.

On an ecoregion basis (Figure 4.1), the Chalk River and Port Hope disposal sites are within the Mixed-Wood Plain Ecoregion area of southern Ontario. The majority of tailings disposal areas, as well as likely deep repository, are located within the Boreal Shield Ecoregion. Smaller areas of tailings in northern Saskatchewan are located within the Boreal Plain and Taiga Shield Ecoregions. Future uranium tailings could be found in these areas of northern Saskatchewan, as well as the Southern Arctic Ecoregion areas of the Northwest Territories (Baker Lake) or Labrador (Makkovik). The areas of these ecoregions are:

- Mixed-Wood Plain
  - Ontario: 13,802,000 ha
- Boreal Shield
  - Ontario: 65,218,000 ha
  - Saskatchewan: 1,000,300 ha
- Boreal Plain
  - Saskatchewan: 25,876,500 ha
- Taiga Shield
  - Saskatchewan: 3,989,000 ha

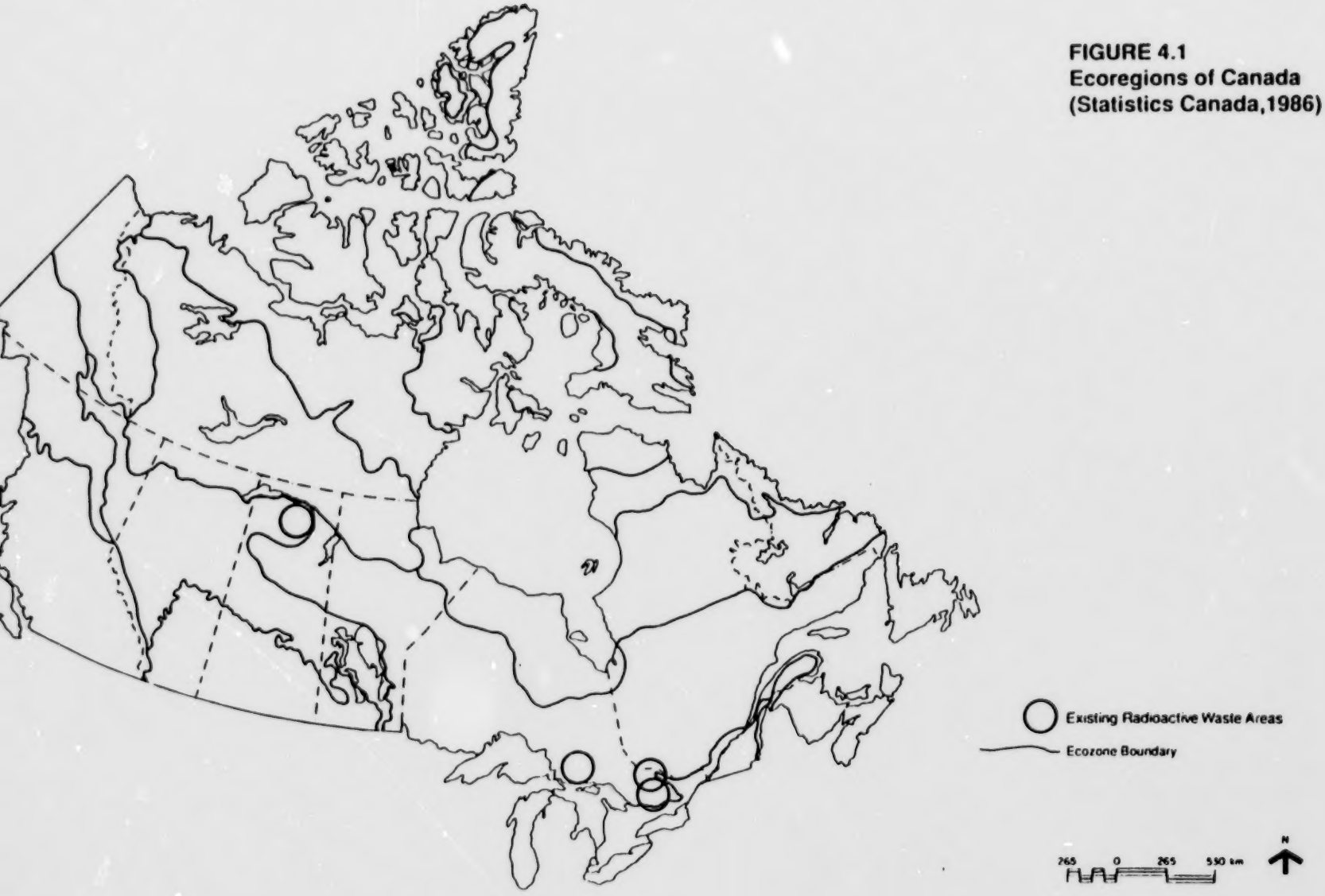


FIGURE 4.1
Ecoregions of Canada
(Statistics Canada,1986)

FIGURE 4.2
Drainage Basins of Canada
(Statistics Canada,1986)

- Southern Arctic
  - N.W.T.: 77,100,500 ha
  - Labrador: 5,622,000 ha

Using the drainage basin subdivisions (Figure 4.2), the Canadian waste sites would be located as follows:

- Uranium Mill Tailings
  - Northern Saskatchewan: Arctic Ocean, Mackenzie River Drainage Area (area = 179,536,500 ha)
  - Elliot Lake: Atlantic Ocean Basin, Lake Huron Shore Drainage Area 182 (area = 5,585,000 ha)
  - Bancroft: Atlantic Ocean Basin, Lake Ontario Shore Drainage Area 161 (area = 1,281,500 ha)

- Chalk River: Atlantic Ocean Basin, Ottawa River Drainage Area 151 (Ontario) (area = 4,263,500 ha)

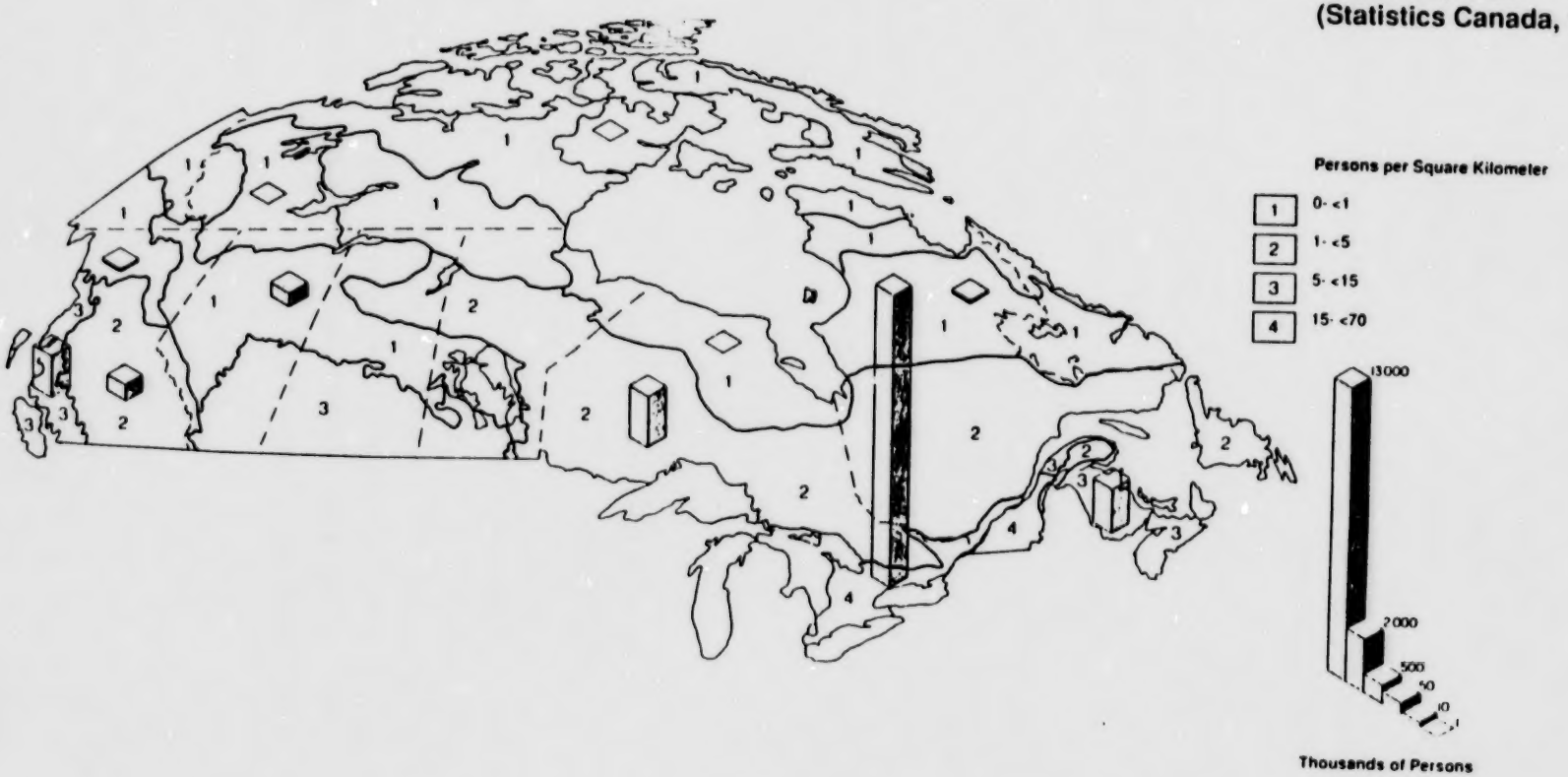
- Port Hope: Atlantic Ocean Basin, Lake Ontario Shore Drainage Area 162 (area = 191,000 ha)

- Northern Ontario Shield: would include portions of about nine drainage basins

4.3 Population Density

Intrusion potential will relate to population density of the area. Figure 4.3 provides statistics data on population by ecoregion as of the 1981 census (Statistics Canada, 1986). For the areas in which radioactive wastes will be or are disposed, the following population statistics are provided:

FIGURE 4.3
Population and Population Density by Ecozones, 1981 (Statistics Canada, 1986)



Disposal Type	(Ecoregion)	Population Statistics for Ecoregion in Which Deep and Surface Disposal Sites Are or Are Proposed to be Located: 1981 Population Total	1981 Population Density ($people/km^2$)	% Population Changes 1976-81
Ontario Deep Disposal	(Bored Shield)	900,487	1	0.6
Chalk River/Port Hope	(Mixed Wood Plain)	7,719,172	56	4.8
Ontario Tailings	(Boreal Shield)	900,487	1	0.6
Saskatchewan Tailings	(Boreal Plain)	136,128	1	0.6

In this case, the drainage basin statistics provide different land use data, as illustrated below:

Disposal Area	Drainage Basin	1981 Population Total	1981 Population Density ($people/km^2$)	% of Population That is Rural
Chalk River	(Ottawa River)	1,298,464	9	29.9
Port Hope	(Lake Ontario)	551,875	115	9.1
Elliot Lake	(Lake Huron)	1,051,119	8	36.2
Bancroft	(Lake Ontario)	551,875	115	9.1
Northern Saskatchewan	(Mackenzie River)	332,747	L 1	43.8

4.4 Mining Regions

Figures 4.4 and 4.5 show the major mining areas in Canada. All of the uranium mill tailings sites, as well as Shield areas of Ontario in which the deep disposal site will probably be located, are areas of significant mining activities. The Port Hope area does not have mining activities. The Chalk River-Ottawa area has limestone quarries, but these are not found in close proximity to Chalk River.

FIGURE 4.4
Coal Mining and Resources, 1983
(Statistics Canada, 1986)

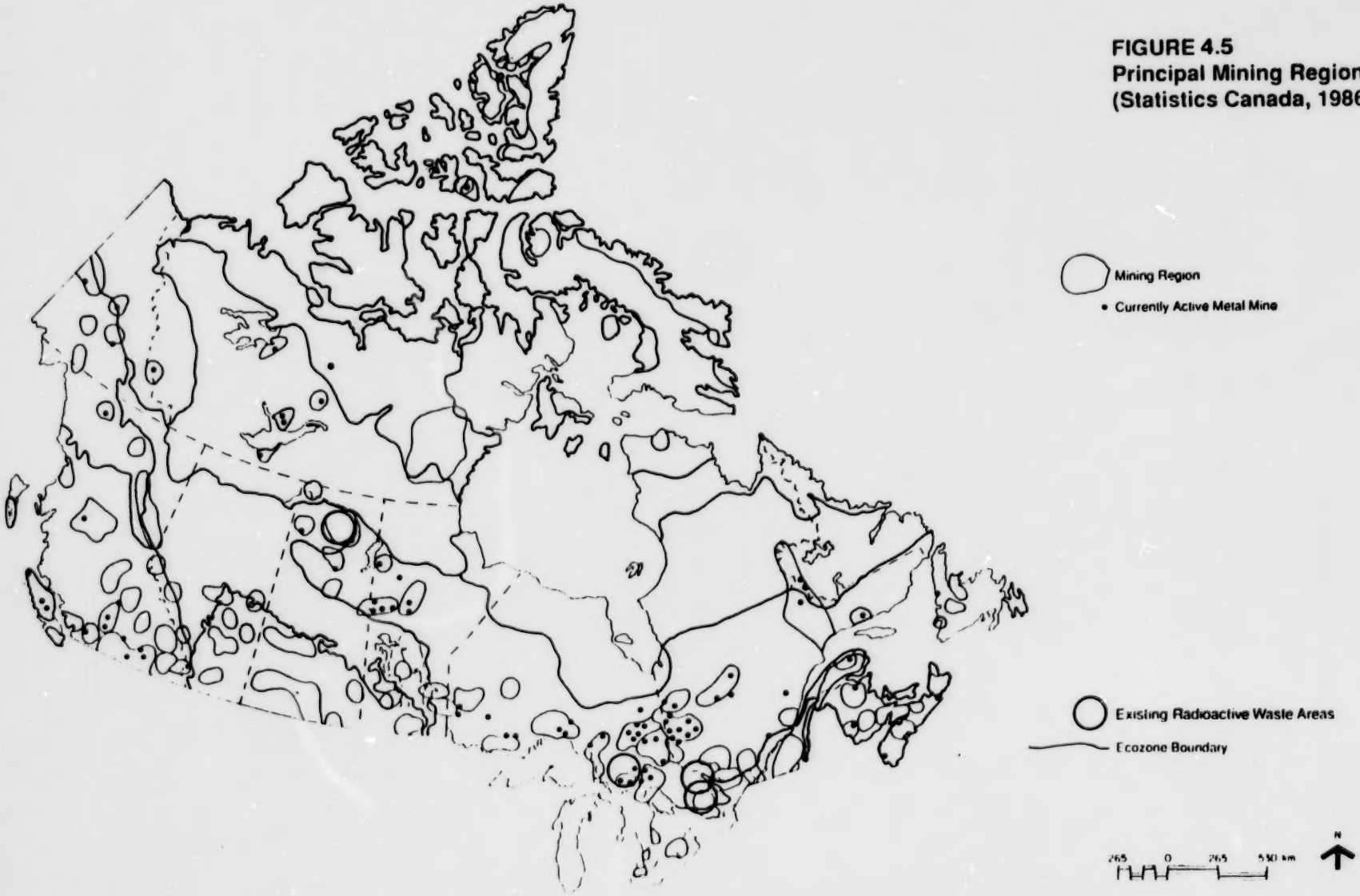


FIGURE 4.5
Principal Mining Regions
(Statistics Canada, 1986)

4.5 Petroleum Exploration

Areas of oil and gas exploration (Figure 4.6) and development (Figure 4.7) in Canada do not coincide with any of the existing nor proposed radioactive waste sites. This intrusion scenario would thus become one of low probability.

4.6 Erosion

Although not strictly an intrusion, concern has been expressed over flooding, water or wind erosion resuspending radioactive wastes to increase the area of potential exposure to intruders. Statistics Canada (1986) indicates that areas of likely radioactive waste disposal in Canada are not found in areas of high surface erosion rates (Figure 4.8).

4.7 Agricultural Use

Soils in Canada have been classified as to their productive potential. The top three classes shown in Figure 4.9 are productive lands, while lower classes are marginal to unproductive with not much potential for agriculture beyond use as pasture. Thus, one can assume the potential for future agricultural intrusion scenarios is much less for lands which are not within these three classes. As shown on Figure 4.9, there are no productive farmlands in areas where uranium mill tailings are disposed or likely to be so in the near future. However, both the Port Hope and Chalk River disposal areas are within or close to prime agricultural lands.

4.8 Summary

Most of the approaches used to date for estimating probabilities of accidental intrusion depend upon extrapolation of present-day land use and population densities. The Statistics Canada (1986) data lend themselves well to supplying raw data for analysis of long-term intrusion probabilities. These methodologies, which use these data, are presented in Section 5.0, with examples of how the data presented above could be used to assess intrusion probabilities for Canadian radioactive waste disposal sites.

FIGURE 4.6
Oil and Gas Production and Exploration Activities, 198 (Statistics Canada, 1986)

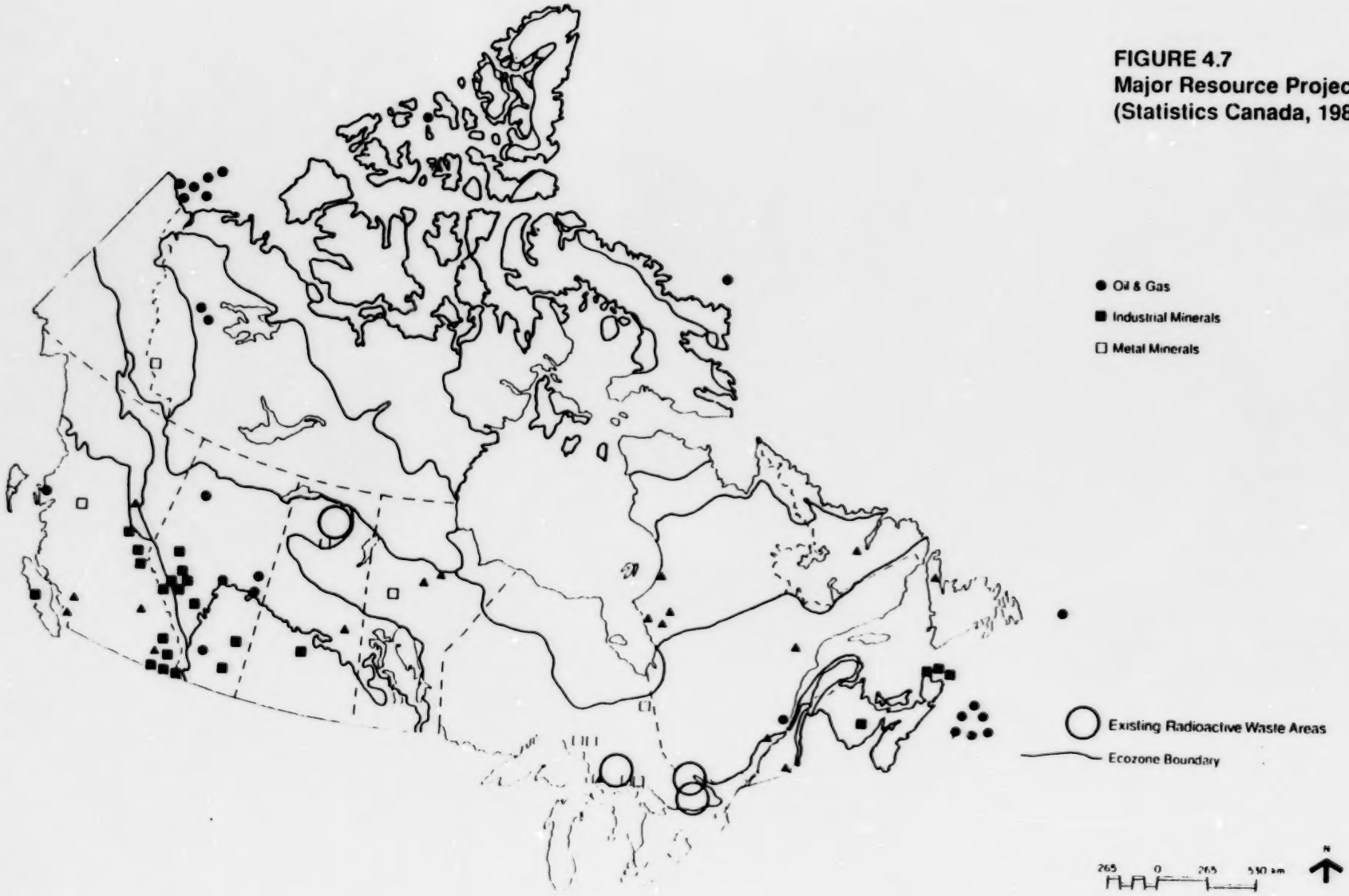


FIGURE 4.7
Major Resource Projects
(Statistics Canada, 1986)

FIGURE 4.8
Water and Wind Erosion
(Statistics Canada, 1986)

FIGURE 4.9
Canada Land Inventory
Agricultural Soil Capability
Classes 1,2 and 3
(Statistics Canada, 1986)

SECTION 5

METHODS USED TO CALCULATE INTRUSION PROBABILITIES

(A REVIEW OF LITERATURE)

5.0 METHODS USED TO CALCULATE INTRUSION PROBABILITIES

Various methods have been used at different stages in the process of calculating intrusion probabilities. Three stages in this process may be recognized, as follows:

1. definition of the system (disposal concept and events that could lead to intrusion),
2. calculation of event probabilities associated with intrusion scenarios, and
3. simulation of the system.

Each of these stages in the process is discussed in detail below.

5.1 Definition of the System

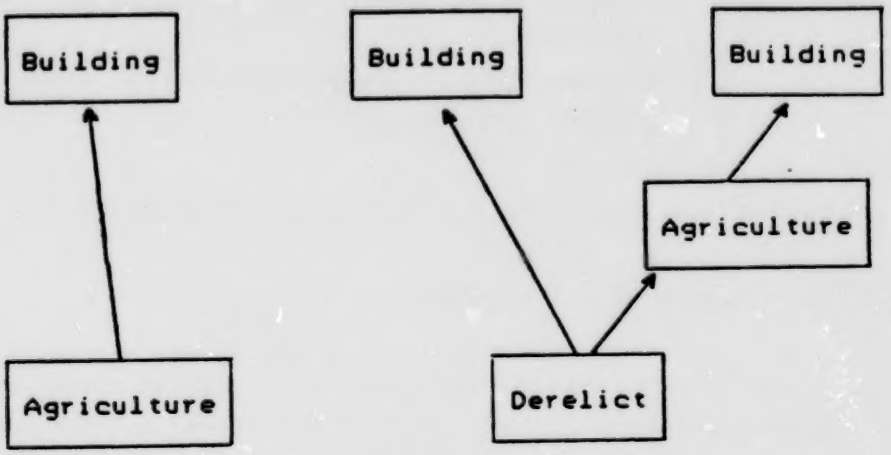
Any probability statement is based on a set of facts or assumptions defining the event to which the statement refers, as well as the universe of other possible events. An event can be any change in state of the systems under study. This system has limits both in time and space (e.g., a particular study area or time period under consideration) which determine the number of possible states the system can achieve. These system limits enter directly into the probability calculations, and should always be explicitly defined as part of the probability statement.

Several methods of initially defining and illustrating the system are in common use. Both fault trees and event trees are used to present the sequences of events which can lead to intrusion, but in different ways. Fault trees start with the event of interest and then work backwards to identify all the combinations of events that may cause the event of interest. Event trees start at the other end by defining all of the different kinds of initial events, and then for each, identify the sequences of events which could follow and, in particular, which of these lead to the event of interest. These approaches are contrasted in Figure 5.1, using an example from Pinner and Hill's (1982) analysis of intrusion into shallow waste disposal sites (see Section 5.2.1). Building on the site is an event assumed to lead to intrusion. Green and Bourne (1972) discuss conventional notation for more complicated event or fault trees.

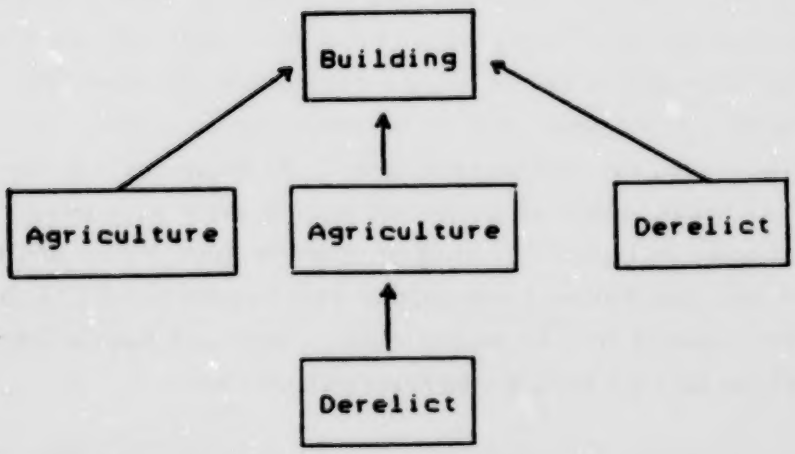
Once the pertinent events have been identified, a probability tree may be used to show the sequences of events (i.e., state transitions) possible in some series of occasions or

FIGURE 5.1: EVENT AND FAULT TREES FOR INTRUSION INTO SHALLOW WASTE DISPOSAL SITES (after Pinner and Hill, 1982)

Event Tree



Fault Tree



'trials' over time, and the probabilities of transition from one state of the system to another in each time period. The probabilities may also be presented in matrix form although, if they change with time, more than one matrix is required.

Figure 5.2 and Table 5.1 illustrate a probability tree and matrix for Pinner and Hill's (1982) analysis. The probability tree includes all possible events, in all possible sequences, which could lead to intrusion over a specified time period. Thus, intrusion is viewed as the final event in a sometimes complex sequence. Many possible sequences could lead to intrusion.

Event probabilities are often conditional (i.e., dependent on preceding events). Therefore, the probability of a certain event occurring within a number of time intervals can be calculated from probabilities of prior events: probabilities are multiplied along each pathway leading to the event of interest (e.g., intrusion), and added over all such pathways.

The event, fault and probability trees are simplified representations of the real system. The more levels and events they contain, the closer they approach a complete representation. However, at some point, the number of events recognized becomes sufficiently large, and our ability to distinguish between them and assign probabilities becomes so small that increased detail is unwarranted. At this point, the limit of our ability to define the system has been reached.

The system should be defined in as much detail as possible, as a first step in calculating intrusion probabilities. This is the critical stage in the process, on which all else depends. The next stage is to calculate event probabilities at the level of detail most appropriate to available data, expertise and intended use.

5.2 Calculation of Event Probabililties

The systems which have been considered in previous attempts to calculate intrusion probabilities have been highly simplified. However, they serve to illustrate a number of different approaches which, in combination, could lead to more sophisticated probability models. Examples of these basic approaches, all deriving intrusion probabilities from current land use trends, are discussed in the following sections.

FIGURE 5.2: PROBABILITY TREE FOR INTRUSION INTO SHALLOW WASTE DISPOSAL SITES (after Pinner and Hill, 1982)

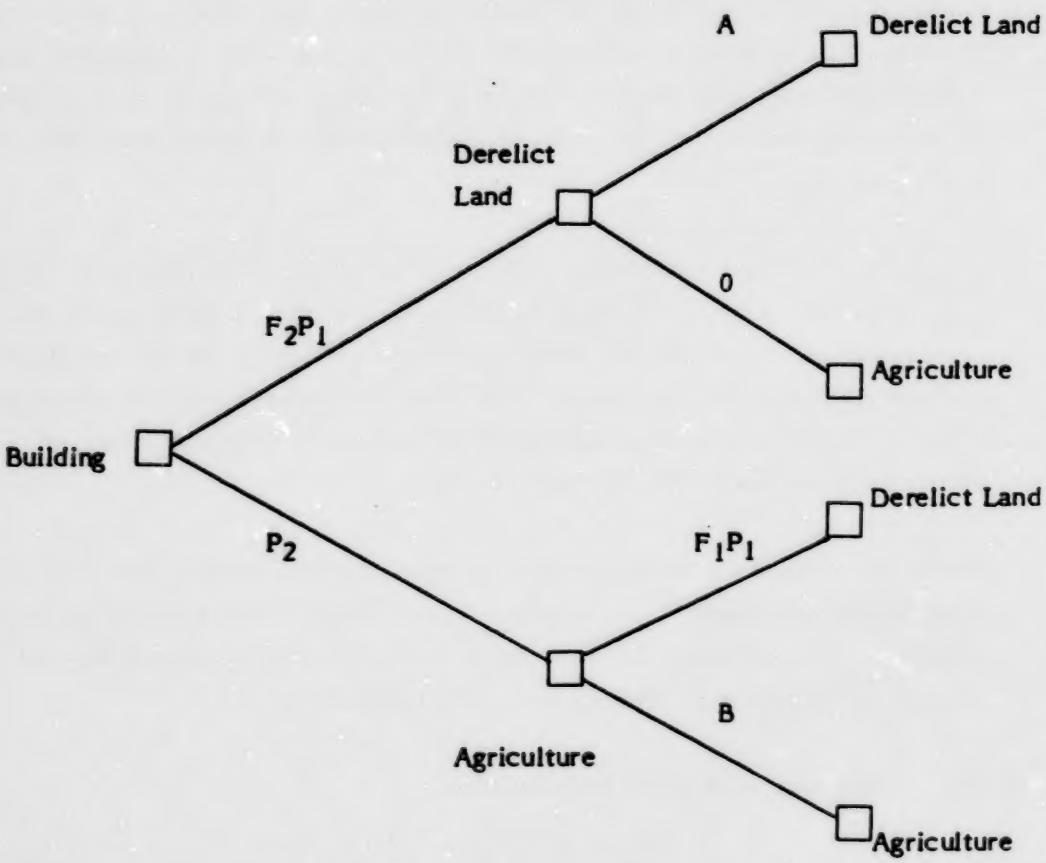


TABLE 5.1: PROBABILITY MATRIX FOR INTRUSION INTO SHALLOW WASTE DISPOSAL SITES (after Pinner and Hill, 1982)

To	Probability of Transition From		
	Derelict Land	Agriculture[1]	Building[2]
Derelict Land	A	0	0
Agriculture	F_1P_1	B	0
Building	F_2P_1	P_2	C

Note: $A = 1 - F_1P_1 - F_2P_1 = q_1$

$B = 1 - P_2 = q_2$

$C = 0$

[1] Agricutural land cannot directly become derelict since derelict land, by definition, is an abandoned building site.

[2] The model terminates when a building is erected, since this is assumed to cause intrusion. Hence, probability of transition from the building state is considered to be zero.

5.2.1 Conditional Probabilities

Pinner and Hill (1982) compute probabilities of intrusion into shallow waste disposal sites by excavation during construction of new buildings. The probability of building on a derelict (i.e., abandoned) waste disposal site is assumed to be the same as the probability of building on any other derelict land, and building on the site is automatically assumed to involve excavation leading to intrusion. Building is considered to occur either directly on the derelict site, or indirectly on agricultural land which has been reclaimed over the site. The probability of building depends on this prior condition of the land.

Building is a terminal event in the probability analysis, since it is assumed to breach the disposal site. At this point, Pinner and Hill (1982) would initiate a deterministic analysis of radionuclide dispersion and dose consequence. The dosimetry model is not considered here.

Figure 5.2 illustrates the probability tree for this system. Table 5.1 illustrates the corresponding probability matrix. The annual probabilities of building on derelict land and agricultural land, respectively, are:

$$P_{db} = F_2 P_1, \text{ and}$$
$$P_{ab} = P_2$$

where: F_1 = the fraction of previously derelict land now farmed,
F_2 = the fraction of previously derelict land now used for building,
P_1 = the current annual reclamation rate for derelict land (either use),
P_2 = the current annual reclamation rate for agricultural land, and
annual reclamation rate = proportion of available land reclaimed in one year.

The probability of farming on previously derelict land is F_1P_1. Pinner and Hill (1982) assume annual probabilities to be constant over the long-term. Thus, they are ignoring any socioeconomic factors that might act to alter rates of land use and thus the probability function. To date, there have been no attempts to incorporate socioeconomic forecasting into intrusion probability analyses.

The universe over which F_1, F_2, P_1 and P_2 are calculated should be appropriate to the geographic region in which disposal is being considered. Pinner and Hill (1982) used land

use statistics for the whole of England and Wales. The universe should not be confused with the disposal site itself. For example, the fractions F_1 and F_2 are not properties of the site; the site is either derelict, agricultural or built upon, and exists entirely in one of these states.

The probability of building on a derelict disposal site in a <u>particular</u> year n since the site was abandoned is computed as:

$$P_b(n) = F_2P_1 (q_1^{n-1}) + F_1P_1P_2 (q_2^{n-2} + q_1q_2^{n-3} + q_1^2 q_2^{n-4} .... + q_1^{n-2})$$

where: $q_1 = 1-P_1$ = the probability of derelict land remaining derelict, and
$q_2 = 1-P_2$ = the probability of agricultural land remaining agricultural.

The first term of this equation represents the probability of the site remaining derelict for n-1 consecutive years, then being used for building. The second term represents the probability of the site becoming agricultural at any time up to n-1 years, then being used for building in year n. Each term takes the standard form of a binomial time series, the first term with one change of state, the second term with two changes occurring over a range of possible time intervals.

The Pinner and Hill (1982) equation can be derived as a specific case of the sub-Markov Chain model (Bhat, 1984). This is a general model for a system with a number of possible states it can be in at different points in time. In the example, there are four possible states for the land: derelict, agricultural, being built on in year n, and built on prior to year n. The first three states are of interest here, since the third state represents the intrusion event of interest. Table 5.1 gives the probability that, if the system is in state j in a given year, it will be in state i the next year. If this matrix is called (P) with three rows and three columns, and elements (i,j), and (V) is the column vector of initial state probabilities, then:

$P_b(n)$ = the row 3 element in $(P)^n (V)$

Thus, for n = 4:

$P_b(4)$ = the row 3 element of $(P)\cdot(P)\cdot(P)\cdot(P)\cdot(V)$.

where: '.' is the symbol for matrix multiplication. The elements of (V) are (1,0,0) if the waste site is assumed to be initially established on derelict land.

In general, the conditional probability of going from state 2 initially to state i in n years is:

$P_i(n)$ = the row i element of $(P)^n$ (V).

where: V = (0, 1, 0). The conditional probability of going from state 3 initially to state i in n years is given by the same equation, but with V = (0, 0, 1).

Details of matrix multiplication can be found in Bhat (1984) or any text on matrix algebra.

Having calculated intrusion probabilities for each year, a risk assessment of the system was performed by Pinner and Hill (1982), in which health risks integrated over 50 years from exposure were multiplied by exposure risks given intrusion, and by the intrusion probabilities $P_b(n)$. The health risks and exposure risks were obtained from a deterministic pathways model.

Sample calculations of intrusion probability for a generic site, following the methods of Pinner and Hill (1982), are illustrated in Table 5.2. Exposure and dose-consequence calculations are not included. Generic site parameters were chosen to be representative of Canadian disposal environments.

5.2.2 Time-Dependent Probabilities

Time-dependence can also be introduced into the sub-Markov Chain model of Section 5.2.1. To make this model time-dependent, a matrix of transition probabilities is required for each time period in the temporal series. In the notation of Pinner and Hill (1982) and Section 5.2.1, the probability of intrusion by building in year n is:

$P_b(n)$ = the row 3 element of $(P)_1 \cdot (P)_2 \cdot (P)_3 \cdots\cdots (P)_n \cdot (V)$.

where: $(P)_n$ is the matrix of transition probabilities corresponding to Table 5.1 for year n, and '·' is the symbol for matrix multiplication.

Sandquist et al. (1986) illustrate the use of time-dependent annual intrusion rates to calculate the cumulative probability of intrusion into low-level waste repositories over a particular time period.

The cumulative probability of one or more intrusions over a period of t years is:

$$P(e \geq 1) = 1 - (1-p)^t$$

where: p = the annual probability of intrusion.

As in Section 5.2.1, a binomial probability model is assumed.

Time-dependence was imposed to reflect an avoidance of the disposal site for a short period following loss of site control. A step-function was used to represent this time dependence of intrusion probability:

Time Period (years)	Annual Intrusion Probability (p)
1-100	$P/10$
101-200	$P/\sqrt{10}$
201- ∞	P

A continuous function for annual intrusion probability could also be used.

Following this step-wise avoidance timetable, a step-wise function for cumulative intrusion probability was derived:

$$P(e \geq 1) = 1 - \left(1 - \frac{P}{10}\right)^t \qquad 0 < t \leq 100$$

$$P(e \geq 1) = 1 - \left(1 - \frac{P}{10}\right)^{100} \left(1 - \frac{P}{\sqrt{10}}\right)^{t-100} \qquad 100 < t \leq 200$$

$$P(e \geq 1) = 1 - \left(1 - \frac{P}{10}\right)^{100} \left(1 - \frac{P}{\sqrt{10}}\right)^{100} (1-P)^{t-200} \qquad t < 200$$

The maximum annual intrusion probability P was separately determined for cropland, pasture and residential land use areas (i) as follows:

$$P_i = F_i C$$

where: F_i = fraction of site land used for purpose i in year 200, adjusting for changes in land use by linear extrapolation of current trends, and

C = maximum fraction of site to be used for waste disposal.

Any co-occurrence of land use and waste was thus assumed to result in intrusion. A separate probability analysis was performed for each of the land use areas.

Sandquist et al. obtained their land use fractions F_i from the U.S. Department of Agriculture, Economic Research Service. The statistics used were for the entire state in which the disposal site would be located. They assumed that a maximum of 1% of the site ($c = 0.01$) would be used for disposal.

Sample calculations of intrusion probability for a generic site following the methods of Sandquist et al. (1986), are illustrated in Table 5.2.

5.2.3 Delphic Probabilities

There may be cases where experts do not agree on formulae for calculation of probabilities of events leading to intrusion, based on land use statistics and waste site characteristics, or on the best statistics to use. Such disagreement can often be traced to differing sets of assumptions, or lack of relevant data. In these situations, a range of opinions must be reduced to a probability statement. This can be done by subjective arbitration or by more objective Bayesian statistical techniques.

Genest and Zidek (1986) have reviewed Bayesian statistical approaches to pooling expert opinion. Many different approaches are possible, depending on the form of the question that the experts are considering, and the desired properties of the pooled concensus. For opinions concerning a single event probability, two fundamental approaches to opinion pooling have been described - linear or logarithmic. Both approaches require the expression of an individual's opinion in the form of a probability distribution.

TABLE 5.2: SAMPLE PROBABILITY CALCULATIONS FOR INTRUSION INTO SHALLOW WASTE DISPOSAL SITES (after Pinner and Hill, 1982)

Input Data

F_1 (fraction of derelict land farmed) = 0.25
F_2 (fraction of derelict land used for building) = 0.75
P_1 (annual reclamation rate for derelict land) = 0.01
P_2 (annual reclamation rate for agricultural land) = 0.005

Probability Calculations

$q_1 = 1-0.01 = 0.99$
$q_2 = 1-0.005 = 0.995$
$P_b(1) = (0.75)(0.01) = 0.00750$
$P_b(2) = (0.75)(0.01)(0.99) + (0.25)(0.01)(0.005) = 0.0074375$
$P_b(3) = (0.75)(0.01)(0.99)^2 + (0.25)(0.01)(0.005)(0.99 + 0.995) = 0.0073755625$

Five-Year Summary of Intrusion Probability

Year	Probability	Cumulative Probability
1	0.00750	0.00750
2	0.0074375	0.01494
3	0.0073755625	0.02231

TABLE 5.3: SAMPLE CALCULATIONS FOR CUMULATIVE PROBABILITY OF INTRUSION WITH TIME-DEPENDENT ANNUAL PROBABILITIES AND AVOIDANCE (after Sandquist et al., 1986)

Asymptotic Annual Intrusion Probabilities (P)

Period (years)	Cropland	Pasture	Residential
1-100	0	0	0
101-200	0.01	0.03	0.002
201-∞	0.02	0.10	0.01

Cumulative Intrusion Probability Calculations

				$Z = (1-P/X)^Y$		
	Period (years)	X	Y	Cropland	Pasture	Residential
t = 50 yrs	1-100	10	50	1	1	1
$P(e \geq 1) = 1 - \Pi(Z)$:				0	0	0
t = 150 yrs	1-100	10	100	1	1	1
	101-200	3.162	50	0.8535	0.6201	0.9689
$P(e \geq 1) = 1 - \Pi(Z)$:				0.1465	0.3791	0.0311
t = 250 yrs	1-100	10	100	1	1	1
	101-200	3.162	100	0.7285	0.3855	0.9387
	201-∞	1	50	0.3642	0.0052	0.6050
$P(e \geq 1) = 1 - \Pi(Z)$:				0.7347	0.9989	0.4321

Π is the symbol for sequential multiplication.

Probability distributions may take the form of discrete probabilities (for several or more mutually exclusive events, e.g., intrusion vs. no intrusion), probability density functions (probability with respect to some reference measure x), or cumulative probability density functions. Care must be taken in pooling expert opinion to ensure that experts are expressing their opinions in the same form.

The linear opinion pool is defined as follows:

$$T(P_i,.....P_n) = \sum_{i=1}^{n} w_i P_i$$

where: T = the pooled concensus probability distribution,
n = the number of experts,
P_i = the probability distribution given by the ith expert, and
w_i = a reliability factor for the ith expert, such that $\sum w_i = 1$.

If P_i is a probability density function of x, with mean m_i, then the mean of the linear pool T is the weighted arithmetic mean:

$$m = \sum_{i=1}^{n} w_i m_i \qquad \text{(Note: } \sum w_i = 1\text{)}$$

Linear opinion pools, based on experience with their use, can be quite variable and are often distributed with several modes. Moreover, they tend to be relatively insensitive to the choice of expert reliability factors.

The logarithmic opinion pool is defined as follows:

$$T(P_i,.....P_n) = N \prod_{i=1}^{n} P_i^{w_i} \quad \text{(Note: } N = \exp\left(\sum w_i \ln \frac{\sqrt{m_i}}{m_i}\right)$$

FIGURE 5.3
Calculation of a Most-Likely Probability Function from Expert Opinions About its Form
(After Mosleh and Apostalakis, 1986)

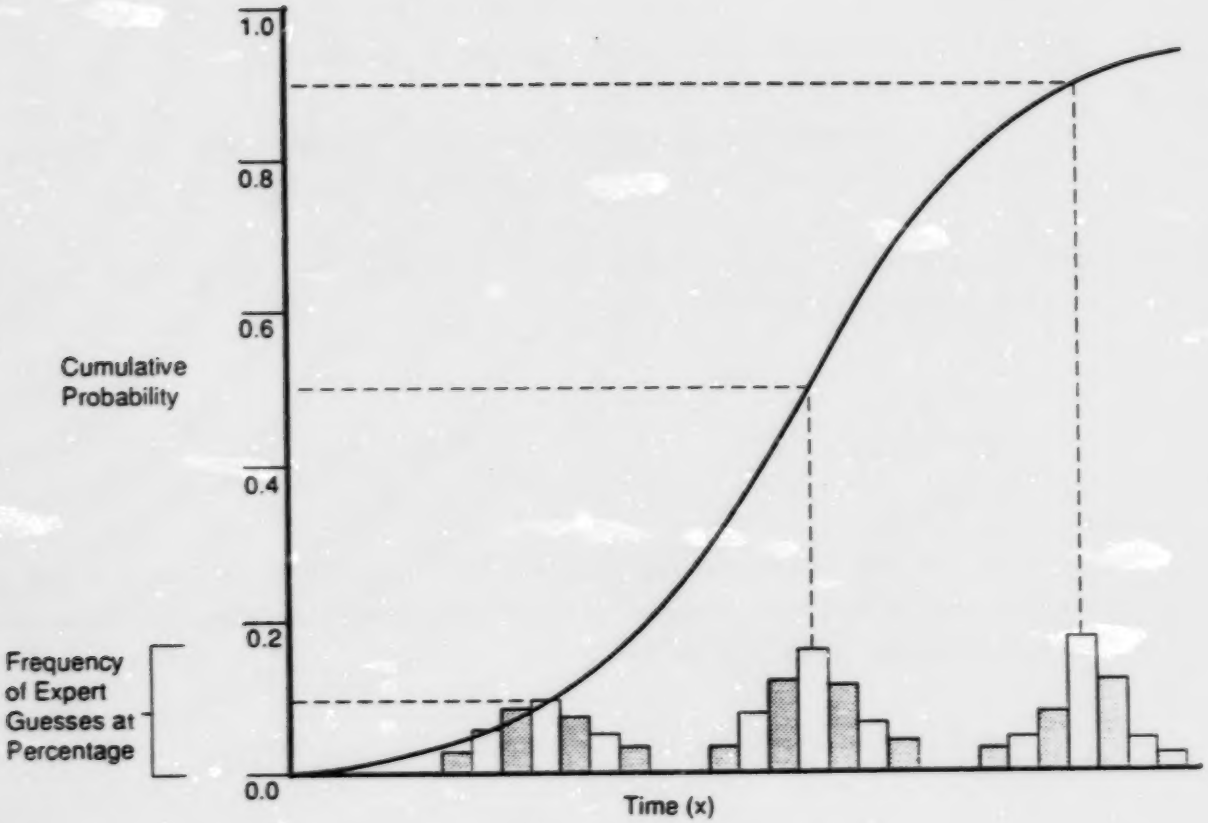


TABLE 5.4: SAMPLE CALCULATIONS FOR POOLING OF LOG-NORMAL PROBABILITY DISTRIBUTIONS DERIVED FROM EXPERT OPINION (after Mosleh and Apostolakis, 1986)

Expert No.	Variance	Values of Percentiles on X-axis 10%	50%	90%
1	4,000	220	510	1,015
2	4,000	245	530	1,080
3	5,000	260	550	1,120
Standard Normal		-1.285	0	1.285
Most Likely $(x \mid \theta, w)$		242.3	510.8	1076.9

Note:

Bias is assumed to be zero.

Intermediate Calculations: $\sigma_\theta^2 = 648.11$

$\sigma_w^2 = 588.75$

$\theta_m = 6.236$

$w_m = 0.582$

Most Likely x From: percent/100 = $\Phi(x|\theta,\omega) = \int_0^x \frac{1}{\sqrt{2\pi}\,\omega x'} \exp\left\{-\frac{1}{2}\left(\frac{\ln x' - \theta}{\omega}\right)^2\right\} dx'$

where N is a normalizing constant, and other parameters are defined as before. If P_i is a probability density function of x, with mean m_i, then following normalization, the mean of the logarithmic pool T is the weighted geometric mean:

$$gm = \exp\left(\frac{1}{n}\sum_{i=1}^{n} w_i \ln m_i\right) \qquad \text{(Note: } \sum w_i = 1\text{)}$$

Logarithmic opinion pools, based on experience with their use, are typically unimodal, and tend to be less dispersed than linear opinion pools. They are generally considered more appropriate representations of expert concensus.

Merkhofer and Keeney (1987) have estimated intrusion probabilities for deep geologic waste disposal sites, based on opinions of an expert panel, however they have not described their opinion pooling process. Pooling methods were referenced to Spetzler and Stael von Holstein (1975).

Mosleh and Apostolakis (1986) describe a logarithmic approach to pooling cumulative probability density functions, based on expert guesses at the percentiles of the cumulative distribution. Figure 5.3 is a generalized graphic representation of that approach in which a 'most likely' probability distribution (assumed log-normal) is estimated from expert opinions about the form (i.e., percentiles) of the true distribution.

The cumulative log-normal probability distribution is defined by:

$$\Phi(x|\theta,\omega) = \int_0^x \frac{1}{\sqrt{2\pi}\,\omega x'} \exp\left\{-\frac{1}{2}\left(\frac{\ln x' - \theta}{\omega}\right)^2\right\} dx'$$

The most likely values of θ and w are:

$$\theta_m = \tfrac{1}{2}\sigma_\omega^2\sigma_\theta^2\Big\{2\Big[(\ln y - \ln b)^T\Sigma_y^{-1}1 + 1^T\Sigma_y^{-1}(\ln y - \ln b)\Big]\left(Z^T\Sigma_y^{-1}Z\right) - \Big[(\ln y - \ln b)^T\Sigma_y^{-1}1 + 1^T\Sigma_y^{-1}(\ln y - \ln b)\Big] \times \left(1^T\Sigma_y^{-1}Z + Z^T\Sigma_y^{-1}Z\right)\Big\}$$

$$\omega_m = \tfrac{1}{2}\sigma_\omega^2\sigma_\theta^2\Big\{2\left(1^T\Sigma_y^{-1}1\right) \times \Big[(\ln y - \ln b)^T\Sigma_y^{-1}Z + Z^T\Sigma_y^{-1}(\ln y - \ln b)\Big] - \Big[(\ln y - \ln b)^T\Sigma_y^{-1}1 + 1^T\Sigma_y^{-1}(\ln y - \ln b)\Big] \times \left(1^T\Sigma_y^{-1}Z + Z^T\Sigma_y^{-1}1\right)\Big\}$$

where:

$$\sigma_\theta^2 \equiv \left(1^T \Sigma_y^{-1} 1\right)^{-1}$$

$$\sigma_\omega^2 \equiv \frac{4\left(1^T \Sigma_y^{-1} 1\right)}{4\left(1^T \Sigma_y^{-1} 1\right)\left(Z^T \Sigma_y^{-1} Z\right) - \left(1^T \Sigma_y^{-1} Z + Z^T \Sigma_y^{-1} 1\right)^2}$$

- y is a vector of N expert values for M percentiles,
- $y^T = (X_{11} \cdots X_{1N}, X_{21} \cdots X_{2N}, \cdots X_{M1} \cdots X_{MN})$,
- T indicates vector transposition,
- b is a vector of bias terms,
- Z is a vector of MxN standard normal percentiles corresponding to expert values in y,
- 1 is an identity vector of length MxN, and
- Σ_y is an (MxN) x (MxN) matrix of covariance between experts corresponding to expert values in y, with individual expert variance (a reliability factor) in the diagonal.

This is a general solution applicable to the situation where expert opinions are intercorrelated. The solution is considerably simplified if experts can be considered independent; however, this assumption is unlikely to be realized.

Sample calculations illustrating the use of this method are provided in Table 5.4. In these calculations, experts are assumed to be unbiased (b = 0 for all experts). A computer program is included in Appendix 1. Expert variance (reliability) is decided prior to performing the calculations, while covariance between experts is calculated from their reported percentile values. Standard normal percentiles are available from statistical tables of the standard normal distribution.

5.3 Simulation Techniques

Once the set of possible event sequences leading to intrusion has been defined (Section 5.1), and the probabilities of those events calculated (Section 5.2), the ultimate probability of intrusion can be computed algebraically by multiplication of probabilities along each pathway, and addition of probabilities across pathways (see Figure 5.3). Probabilities can be expressed either on an annual or cumulative basis. It is important to

include this basis of expression in the probability statement, along with the assumptions inherent in the probability calculations.

Annual probabilities can be incorporated into a stochastic event sequence simulation model, using Monte Carlo techniques. Doll and Freeman (1986) describe the general Monte Carlo approach, in which events are allowed to occur (or not occur) at each time step, according to their probabilities. Probabilities may be conditional on occurrence of prior events, as discussed in Section 5.2. Each run of a Monte Carlo model can produce a different event sequence. Over many runs, the frequency of event occurrence should approximate the input event probabilities.

Deterministic consequences of intrusion events, such as radiation dose commitments, can easily be incorporated into the Monte Carlo model, so that over many model runs the upper and lower limits of potential dose commitment can be determined for any time following abandonment of the waste disposal site. Harper and Raines (1985) illustrate the use of a Monte Carlo model to generate 95% confidence limits for radionuclide release as a consequence of intrusion by drilling into high level nuclear waste repositories.

For simple models, computer simulation may not be necessary to an understanding of model behaviour, since calculations are easily performed by hand. However, for more complex models, computer simulation may be required. It is always useful to examine the effect of changing the assumed annual probabilities for various events, and computer simulation can simplify this task.

Holling (1978) describes a simulation technique that could be used either to simulate intrusion directly or to understand the net effect of complex interactions on time-dependence in probabilities of events leading to intrusion. Most intrusion analyses acknowledging that probabilities may change with time have been restricted to very simple temporal relationships (e.g., step-functions, continuous linear functions or simple exponentials). In reality, multiple societal factors may interact in complex fashion to influence event probability and occurrence. While it may be difficult to envisage the net effect of these interactions, pairwise interactions between societal factors can be more easily surmised. The cross-impact simulation algorithm (KSIM) described by Holling permits estimation of such complex time trends from a factor interaction matrix. Its

main use might be in establishing realistic forms of time-dependence functions prior to formal probability analysis.

A hypothetical example of a KSIM interaction matrix is given in Table 5.5. Coefficients (a_{ij}) from -1 to 1 indicate the direction and relative magnitude of interactions between societal factors. One of these factors is the event of interest, whether intrusion or some other event. Values of each factor (X_i), however quantified, are normalized over the range (0, 1) representing the minimum to maximum possible. At each time step, the following calculation predicts the next value of factor X_i from current factor values:

$$X_i(T + \Delta t) = X_i(T)^{\Phi_i(T)}$$

where:

$$\Phi_i(T) = \frac{1 + \frac{\Delta t}{2} \sum_{j=1}^{m} (|a_{ij}| - a_{ij}) X_j(T)}{1 + \frac{\Delta t}{2} \sum_{j=1}^{m} (|a_{ij}| + a_{ij}) X_j(T)}, \text{ and}$$

m = the number of column variables.

Only first-order interactions between factors are considered in this formulation. Second and higher order interactions are easily included by addition to the a_{ij} above.

A sample simulation, based on the information in Table 5.5, is illustrated in Figure 5.4. A computer program is included in Appendix 1. The simulation shows that the site will eventually be used entirely for buildings. Once building reaches saturation, intrusion stabilizes at its maximum since intrusion results only from new building projects.

5.4 The Role and Limitations of Probability Analysis

Probability analysis will be used to compare and evaluate different waste disposal options in terms of intrusion risk and consequence. It must be recognized that the validity of the analysis depends on the validity of all the assumptions made. Assumptions regarding land

use and other societal trends may be particularly important and difficult to support. Probability statements are meaningful and comparable only if these assumptions are explicitly included in the statement.

If there are significant intrusion events over the long-term that were not predicted by the model, it will likely be because of some false assumption or some factor not accounted for in the modelling which was reflected in the design and siting of the waste repository. It, therefore, seems important to devise ways of keeping track of waste repository locations over future generations. This may be more important for future safety than reassuring calculations prior to disposal, based on assumptions that things will change only in foreseen ways.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

6.0 CONCLUSIONS AND RECOMMENDATIONS

The assessment of future risks associated with accidental intrusion into a nuclear waste site consists of two distinct components. The first is an assessment of the probability of an accidental intrusion occurring, and the second is an assessment of the detriment occurring as a result of that intrusion.

A review of the literature has shown that very few authors, in assessing the risks arising from future accidental intrusion into a nuclear waste site, have used any sort of formal methodology in calculating the actual probability of intrusion.

6.1 Conceptual Approaches

The majority of authors have taken the approach of making the assumption, or assigning a probability of one, that an accidental intrusion will occur. Then, based upon the assumption that intrusion will occur, the authors have calculated the detriment resulting from a series of intrusion exposure scenarios.

The next level of approach has been, based upon an arbitrary assumption or an extrapolation of present-day activities, to calculate an annual probability of intrusion based upon a given activity. The activity may be exploratory drilling for intrusion into a deep geological repository or urban construction in the case of an intrusion scenario for a near-surface or surface facility. The simplest approach was for researchers to assume a uniform annual probability beginning at the time of loss of institutional control and continuing until the cumulative probability attains a value of one.

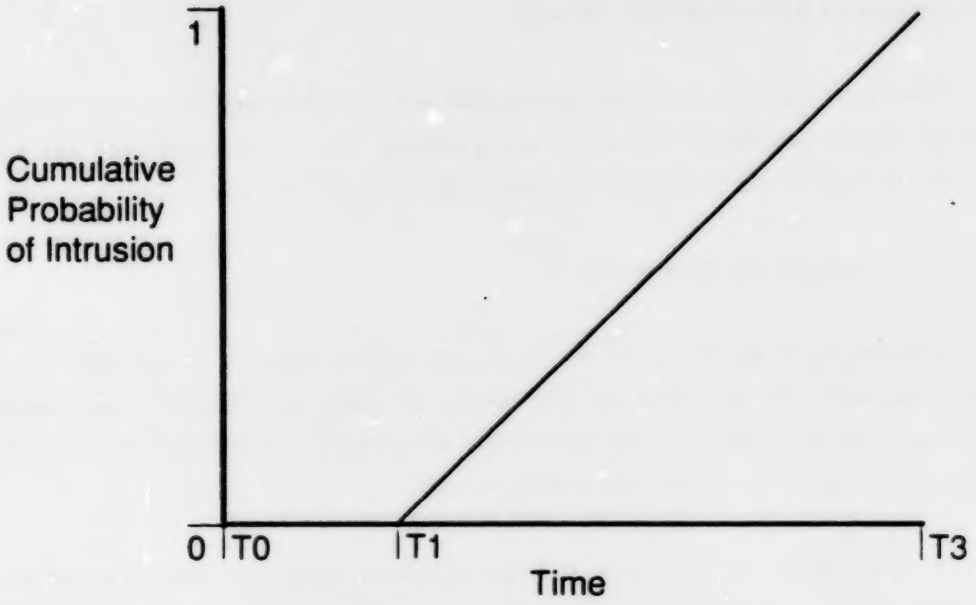
The highest level of sophistication was obtained by authors who used discounted probabilities to try and take into account societal factors. That is, in the early years of the assessment beginning at the termination of institutional control, the annual intrusion probability is discounted to reflect a residual local knowledge or some other factor that may deter accidental intrusion. These two approaches can perhaps be best illustrated graphically as in Figure 6.1.

Most of the differences variation in analysis between accidental intrusion scenarios discussed in the literature related to how one determines the linear slope or variable

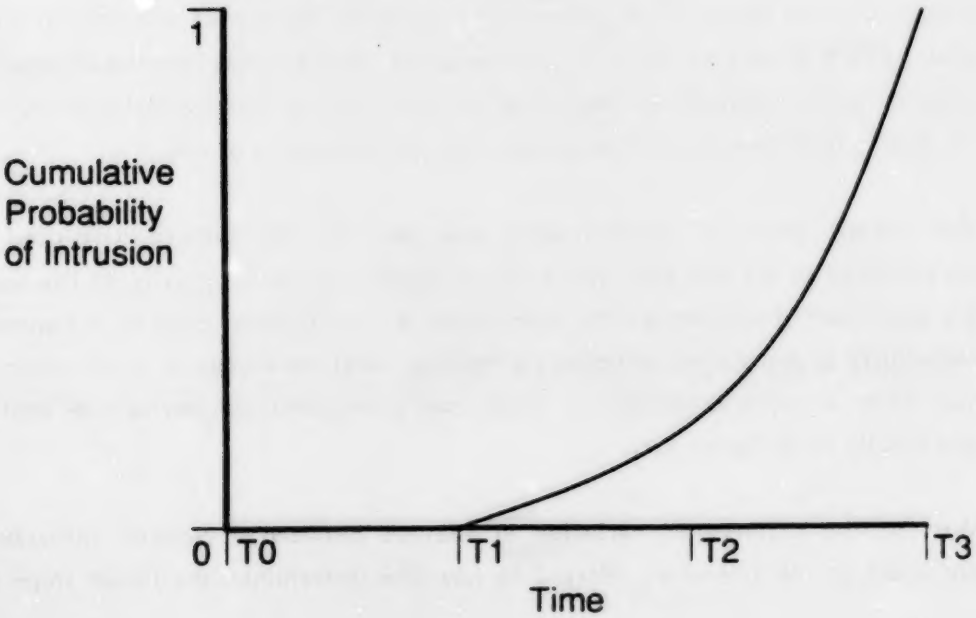
FIGURE 6.1
Linear and Non-Linear Cumulative Probability Functions Terminating at P=1

LEGEND: Times - T_0= disposal; T_1= loss institutional control; T_2= increasing p; T_3= maximum p.

(a) Linear Function



(b) Non-Linear Function



form of the variable function describing change in annual probabilities with time. In determining the nature of this probability function, the most common approach was to choose a specific scenario such as deep exploratory drilling as a possible intrusion scenario. Then, based upon the recent drilling history in the area (state, province, ecoregion, etc.), quantify a drilling rate (i.e., x deep holes/a/area) and assume this rate would occur into the indefinite future. The specific scenario would then define an intrusion event to occur if drilling occurs in an intrusion zone which occupies a specific area, (i.e., 10 km^2). In this example, the annual intrusion probability for the region would then be:

$$\frac{\text{the intrusion zone area}}{\text{total area of the region}} \times \text{number of holes in the region/a} .$$

and, at some time in the future, the cumulative probability of intrusion would be one.

If any of the parameters in these calculations are considered variable with time then annual intrusion probabilities will also vary. In the example above of a deep repository, the intrusion zone at T_o (time at which institutional control lapses) may consist of (say 1,000 m^2) the total area of waste canisters exposed in a vertical direction. At some time in the future, after the canisters have disintegrated and wastes spread throughout the repository area, the intrusion zone may be 10,000 m^2 and hence the annual intrusion probability will have increased. In this example, there may be a break in the probability curve at the point when one of the variables (intrusion area) begins to change (i.e., when cannisters begin to leak). There are many variations on this approach, depending upon the particular scenario selected for analysis.

A third possible type of conceptual approach that was not found in the literature would involve the limiting of the cumulative probability function. This could work in the following manner for the scenario of, for example, urban encroachment onto old uranium mill tailings. As in the previous example, a reference area or universe is selected. This may be, for example, a province or country or some other land area. Within this reference area, there will be a fixed area of uranium mill tailings. A review of recent activities (e.g., Statistics Canada reports) will show a rate of urbanization (i.e., a certain area per year being developed for urban use within the reference area) which is not constant or increasing, but declining asymptotically toward zero. At this point, a

function describing the reduction in annual probability with time could be generated. This third approach differs from those which have been used, however, by making the assumption that there is a limit to the percentage of the total land mass that may be urbanized (or indeed subjected to any other potential intrusion activity). The nature of this limit will be a function of socio-economic processes which define a need for park lands, national parks and need for land to be used for purposes other than urbanization. If the reference area was Canada, one would like to think that no more than say 20% of the country would ever be covered by suburbs. For other examples, such as oil exploratory drilling, the limit to commercial field size may dictate that drilling ceases in a reference area once the field is fully explored or exhausted. Thus, depending upon the scenario selected, the cumulative probability curve may plateau at a value less than one, suggesting that intrusion is not simply a question of time. That is, there is a probability that it may never occur. This type of curve could be illustrated as in Figure 6.2.

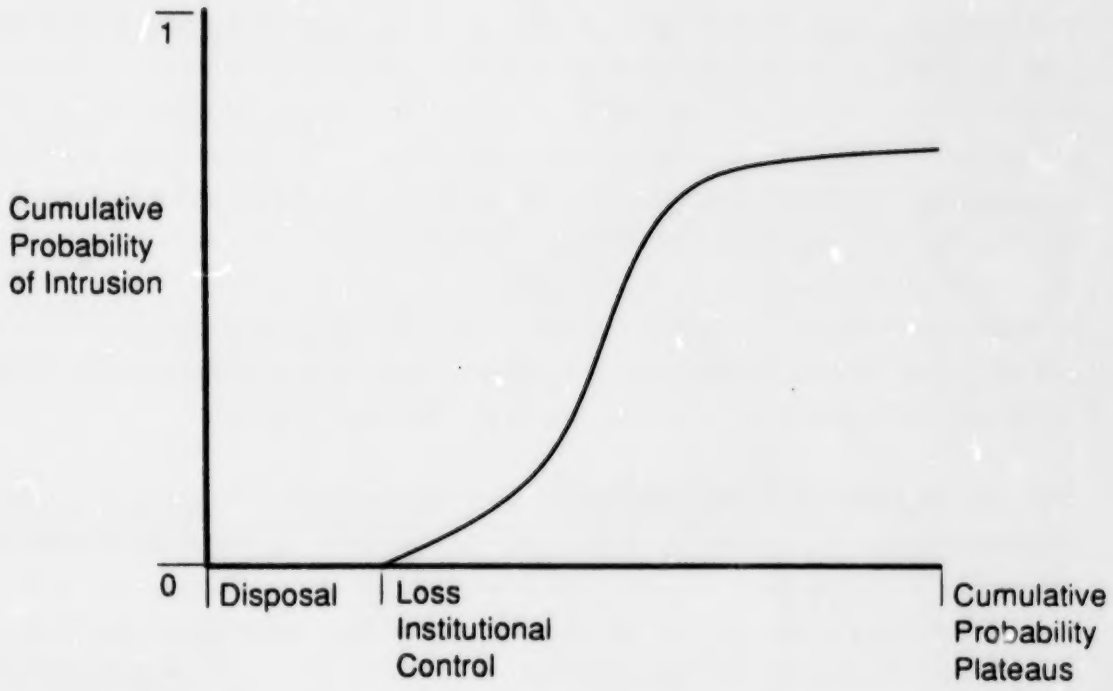
6.2 Probability Analysis Methods

Several conceptual approaches have been described to estimate the probability of intrusion into waste disposal areas over the long-term. Probability analysis could be based on any one of these approaches, depending on the waste disposal, intrusion scenarios considered and degree of sophistication justified. The key item is the way in which assumptions are made for unmeasurable or forecast model parameters and how these are documented. The limitations resulting from such assumptions must be emphasized, and study conclusions viewed in light of these limitations and assumptions.

The first step in these analyses is to prepare a definitive list of the potential events leading to intrusion, within each intrusion scenario. For each of these events, annual probabilities must be assigned. These in turn can be combined to give a cumulative probability of intrusion over a longer term. In order to determine these probabilities, important unmeasurable parameters must be specified and dimensions assumed based on best scientific/engineering knowledge available. These assumptions and limitations must be defined with any probability statement. In Section 5.0, we have proposed a probability tree approach to formalize this step in the analysis.

All of the current methods for analyzing future intrusion probabilities are based on current land/resource use trends for the reference area in which the waste management

FIGURE 6.2
Non-Linear Probability Function
Terminating with P<1



area is located. Section 5.0 provides examples of how this has been done by past researchers. Canadian land/resource use data of relevance to such analyses are summarized in Section 4.0. The accuracy of the probability function will be dependent upon the amount of site-specific data used and the relative size of the reference area. A good example of this need for site-specific information relates to the Chalk River shallow land burial site. The small-scale maps in Section 4.0 would lead one to conclude the large reference region had a high agriculture potential, as well as limestone quarry potential. A smaller reference region would indicate predominantly sandy surficial materials with limited agricultural potential. The limestone resources are further south, near Ottawa.

Three methods of assigning annual probabilities and describing cumulative probability functions based on current land/resource use knowledge are described and demonstrated in Section 5.0. One method by Pinner and Hill (1982) illustrates the use of conditional probabilities in which the probability of intrusion in any one year depends on the current state (i.e., land use) of the abandoned disposal site. However, these annual probabilities remain constant from year to year. A second method by Sandquist et al. (1986) illustrates the use of time-dependent probabilities. In this method, cumulative probabilities of intrusion occurring, as time passes, are calculated based on expectation of changing (increasing) annual probabilies of intrusion as time from disposal passes. The third method illustrated is a Delphic approach. Several authors propose different variations on the Delphic approach in which a panel of experts goes through an iterative process to reach a professional concensus concerning the form of the probability function for an intrusion event, or other events potentially leading to intrusion.

Once probabilities have been assigned to each of the factors affecting the ultimate intrusion probability, simulation techniques may be used to model occurrence (and consequence) of intrusion over time. Two simulation techniques are discussed in Section 5.0. Monte Carlo techniques may be used for quantitative probabilistic simulation, and Cross-Impact Simulation techniques may be used for deterministic projection of relative time trends in interacting system parameters.

6.3 Recommendations

In forecasing future risks associated with accidental intrusion into waste disposal sites, it is recommended that the first step be to conservatively assume a cumulative intrusion probability of one for the first year following loss of institutional control. Based upon the nature of the accidental intrusion specified, a detriment is calculated. If the detriment exceeds regulatory limits, then the first step is to attempt to secure the design of the site such that a reasonable accidental intrusion scenario would not result in an unacceptable level of detriment. If all reasonable measures are taken and the detriment resulting from an accidental intrusion is still unacceptable, then proceeding to a more sophisticated level of analysis may be justified.

The next step would be to collect and analyze the necessary data in order to generate a cumulative probability function describing future accidental intrusion, which plateaus at a value of one, using one or more of the methodologies described in Chapter 5.0. Based upon this function, simulation techniques may be used to generate intrusion occurrences that then can be coupled with time-dependent detriment calculations (e.g., allowing for decay or waste dilution) in order to generate overall risk calculations. If the necessary level of 'safety' can be demonstrated with this approach, proceeding to a more sophisticated level of analysis is probably not justified.

If justified, a third level of sophistication in analysis could be entered into in which a cumulative probability function which plateaus at a value of less than one is generated. A similar type of analysis using simulation techniques could then be carried out and a decision based upon these results.

In summary, it is recommended that, because the collection of the appropriate data needed to generate accidental intrusion probability functions can be expensive, and the data arising from any exercise in predicting the future can always be disputed, analysis of sites using more sophisticated procedures only be entered into where justified. The nature of this justification lies within the concept of the need to optimize repository design. Accidental intrusion probability analysis can be a valuable tool in this optimization exercise where conjecture about future events can often cloud the real issue being addressed (i.e., the current 'safe' design of waste management facilities that will also provide a specified future level of safety occurrence).

SECTION 7

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7.0 REFERENCES

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7.2 Personal Communications

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APPENDIX 1

Programs for KSIM Trend Projection and Expert Opinion Pooling

```
      program ksim

* Intrusion analysis

      real deltat,totime,a(3,3),phi(3),x(3)
      real sum1(3),sum2(3)

* deltat - time step
* totime - total time of simulation
* a(*,*) - interaction matrix
* x(*)   - values at this time step

      open(1,file='ksim.dat',status='old')

      read(1,*)deltat
      read(1,*)totime
* need to read 'a' and 'x'
      read(1,*)
      do 50 i=1,3
50        read(1,*)(a(i,j),j=1,3)
      read(1,*)
      read(1,*)(x(i),i=1,3)

      t=0
      icount=1

      print*,'time step =',deltat
      print*,'a matrix'
      do 5 i=1,3
5       print*,(a(i,j),j=1,3)
      print*,'x initial'
      print*,(x(i),i=1,3)
      print*,' '
      print*,'time    x1    x2    x3'


10    continue
      do 30 i=1,3
        sum1(i)=0
        sum2(i)=0
        do 30 j=1,3
          sum1(i)=sum1(i)+(abs(a(i,j))-a(i,j))*x(j)
30        sum2(i)=sum2(i)+(abs(a(i,j))+a(i,j))*x(j)
      do 20 i=1,3
        phi(i)=(1+deltat/2*sum1(i))/(1+deltat/2*sum2(i))
        x(i)=x(i)**phi(i)
20    continue

      t=int((t+deltat)*100.01)/100.
      if(icount.eq.10) then
        print*,t,(x(i),i=1,3)
        icount=0
      endif
      icount=icount+1

      if(t.le.totime-deltat) goto 10

      end
```

```
.01     delta time
25      total time
'a' matrix
 .2  -.5  0.
-.1   .4  0.
 0.   .8  0.
'x' init
.2  .1  .01
```

```
      program cdf

* Assesment of probability Distributions from expert opinions

      implicit real*8 (a-h,o-z)

      real*8 y(9),Ey(9,9),EyIn(9,9),Id(9)
      real*8 z(9),temp(81),lny(9)


* build identity vector

      do 10 i=1,9
10      Id(i)=1

* read in input values

      open(1,file='cdf.dat',status='old')

* y - expert values
      read(1,*)
      read(1,*)(y(j),j=1,9)

* z - standard normals for percentiles
      read(1,*)
      read(1,*)(z(i),i=1,9)

* read reliability factors
      read(1,*)
      read(1,*)(Ey(i,i),i=1,3)
* calculate covariances between experts put into Ey
      call fixEy(Ey,y)

* invert matrix
      call invert(Ey,EyIn,9)


      o2theta=0
      do 30 i=1,9
        do 30 j=1,9
30        o2theta=o2theta+EyIn(i,j)
      o2theta=1/o2theta

* calculate o2w

* compute t1
      t1=0
      do 40 i=1,9
        do 40 j=1,9
40        t1=t1+EyIn(i,j)

* compute t2
      call mult(z,Eyin,temp,1,9,9)
      call mult(temp,z,t2,1,9,1)

* compute t3
      call mult(Id,Eyin,temp,1,9,9)
      call mult(temp,z,t3,1,9,1)

* compute t4
      call mult(z,Eyin,temp,1,9,9)
      call mult(temp,Id,t4,1,9,1)

* now finish
      o2w=4*t1/(4*t1*t2-(t3+t4)**2)
```

```
* calculate theta

* compute lny
      do 50 i=1,9
 50     lny(i)=dlog(y(i))

* compute t5
      call mult(lny,Eyin,temp,1,9,9)
      call mult(temp,Id,t5,1,9,1)

* compute t6
      call mult(Id,Eyin,temp,1,9,9)
      call mult(temp,lny,t6,1,9,1)

* compute t7
      call mult(z,Eyin,temp,1,9,9)
      call mult(temp,z,t7,1,9,1)

* compute t8
      call mult(lny,EyIn,temp,1,9,9)
      call mult(temp,z,t8,1,9,1)

* compute t9
      call mult(z,EyIn,temp,1,9,9)
      call mult(temp,lny,t9,1,9,1)

* now compute results

* first theta

      theta=o2w*o2theta/4*(2*(t5+t6)*t7-(t5+t6)*(t3+t4))
* now w

      w=o2w*o2theta/4*(2*t1*(t8+t9)-(t5+t6)*(t3+t4))


      print*,' '
      print*,' '
      print*,'o2w = ',o2w
      print*,'o2theta = ',o2theta
      print*,' '
      print*,'theta = ',theta
      print*,'w = ',w


      end
*******************************************************************************
      subroutine mult(a,b,c,i1,i2,i3)
      implicit real*8 (a-h,o-z)

* matrix multiplication

      real*8 a(i1,i2),b(i2,i3),c(i1,i3)

      do 10 ii1=1,i1
        do 10 ii3=1,i3
          sum=0
          do 30 ii2=1,i2
 30         sum=sum+a(ii1,ii2)*b(ii2,ii3)
          c(ii1,ii3)=sum
 10   continue

      end
*******************************************************************************
      subroutine invert(a,ainv,n)
```

```
c
* matrix inversion

        integer r,c,n
        real*8 a(n,n),ainv(n,n),t,y,s
c
        do 10 c=1,n
          ainv(c,c)=1.
   10   continue
c

        do 20 r=1,n

* find non zero at this spot on diagonal
         t=a(r,r)
         if(t.ne.0.) goto 31
         do 25 c=r+1,n
          if(a(c,c).ne.0.) goto 26
 25      continue
         goto 70
* swap zero with non zero
 26      continue
          do 30 k=1,n
            s=a(r,k)
            a(r,k)=a(c,k)
            a(c,k)=s
            s=ainv(r,k)
            ainv(r,k)=ainv(c,k)
            ainv(c,k)=s
   30     continue
   31     continue
* divide to get 1 at this spot on the diagonal
          do 40 k=1,n
            a(r,k)=a(r,k)/t
            ainv(r,k)=ainv(r,k)/t
   40     continue
* now zero out other columns by subtracting multiples of this row
          do 50 l=1,n
            if (l.eq.r) goto 50
            y= a(l,r)
            do 60 k=1,n
              a(l,k)=a(l,k)-y*a(r,k)
              ainv(l,k)=ainv(l,k)-y*ainv(r,k)
   60       continue
   50     continue
   20   continue
        return
c
   70   write(*,*) 'Matrix Univertible'
        return
        end
*****************************************************************************
        subroutine fixEy(Ey,y)
        implicit real*8 (a-h,o-z)

* calculate covariances and replicate along diagonal sub-matrices

        real*8 Ey(9,9),y(3,3),ave(3)

* calculate averages

        do 4 i=1,3
 4        ave(i)=0

        do 5 i=1,3
```

```
5          ave(j)=ave(j)+y(i,j)/3

* now find covariances
        do 10 i=1,3
          j=i+1
          if(j.eq.4) j=1
          sum=0
          do 20 k=1,3
20          sum=sum+(y(k,i)-ave(i))*(y(k,j)-ave(j))
          sum=sum/2
          Ey(i,j)=sum
          Ey(j,i)=sum
10      continue

* replicate sub covariance matrix along diagonal

        do 60 i=1,2
          do 60 j=1,3
            do 60 k=1,3
60            Ey(3*i+j,3*i+k)=Ey(j,k)

        end
```

```
y matrix
220  245  260
510  530  550
1015 1080 1120
z vector
-1.285 -1.285 -1.285 0.0 0.0 0.0 1.285 1.285 1.285
Expert diagonal
4000 4000 5000
```